

# CIRCUMSTELLAR DISKS AROUND PRE-MAIN-SEQUENCE STARS: WHAT ISO CAN TELL US

A. Natta

*Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5 I-50125 Firenze,  
Italy*

M.R. Meyer and S.V.W. Beckwith

*Max Planck Insitut für Astronomie, Heidelberg, Germany*

**Abstract.** ISO observations will improve our understanding of disks around low-mass pre-main-sequence stars in various ways. In particular, ISO can measure simultaneously spectral energy distributions and low-resolution spectra from 2 to 12  $\mu\text{m}$  of T Tauri stars with greater sensitivity, greater spectral coverage and finer spectral resolution than available in ground-based observations or with IRAS. We illustrate the importance of such observations for our understanding of the disk structure and heating mechanisms, the disk evolution (in particular the formation of gaps caused by the presence of companion stars or large planets) and dissipation using preliminary results from PHOT and PHOT-S for T Tauri stars in the Chamaeleon cloud.

## 1. Introduction

Circumstellar disks around low mass pre-main-sequence stars (T Tauri stars, TTS) have been at the center of attention for quite a long time. Disks are believed to account for the infrared and millimeter wavelength excess emission seen in TTS; if accretion of matter from the disk onto the star occurs, some of the accretion energy can be emitted as hot continuum radiation explaining the observed UV excess (see, for example, Hartigan et al. 1995); accretion in a keplerian disk, coupled to strong magnetic field, can lead to ejection of matter from the system and couple the angular momentum of the star to that of the disk, explaining the puzzling behaviour of the rotation periods of TTS (see the recent review by Edwards 1997).

The picture of the distribution and evolution of the matter surrounding low-mass young stars which emerges from the wealth of recent studies is quite complex. The infrared properties of TTS have been particularly important in shaping our ideas about disks. When compared to the observations, the infrared spectral energy distribution (SED) of a standard (i.e., geometrically thin, optically thick) model disk, either heated by dissipation of viscous energy or by the stellar radiation, tends to produce too much flux at short wavelengths, and too little at long wavelengths. The first problem is solved by inserting a hole

in the inner accretion disk (Meyer, Calvet & Hillenbrand 1997). Such holes are predicted in magnetospheric accreting models where the stellar magnetic field disrupts the inner parts of the disk up to distances from the star of few stellar radii and channels the accreting matter along magnetic flux lines (see Kenyon, Yi & Hartmann 1996 and references therein). The observed excess emission at long wavelengths in comparison to model predictions may be accounted for (at least partially) by the flaring of disks at large distances from the star (Kenyon and Hartmann 1987); other effects of importance are the action of extended layers of optically thin dust associated with the optically thick disk, possibly due to disk winds (Natta 1993) or residual infalling matter (Natta 1993; Calvet et al. 1994; D'Alessio et al. 1997), and the formation of a disk atmosphere in hydrostatic equilibrium (Chiang and Goldreich 1997; see also Calvet et al. 1992).

In this paper, we will briefly discuss the areas in which ISO will provide significant contributions to our understanding of the disk physical structure, lifetime and dissipation.

The imaging capability of ISO has been used to survey regions of star formation at different wavelengths. These surveys are expected to yield a complete census (to lower sensitivity limit than ground-based observations) of young stars *with* circumstellar disks in several regions of star formations. Nordh et al. (1996; this conference) have presented the first results of a survey at 6.75 and 15  $\mu\text{m}$  of the Chamaeleon region obtained with CAM which illustrates the potential of ISO in this field. We refer to their work for further details.

Several ISO programs plan to measure the SEDs of well-known TTS. They plan to take advantage of the greater ISO sensitivity, greater spectral coverage and finer spectral resolution than available in ground-based observations or with IRAS. It is in many cases important to determine the shape of the SED simultaneously at all wavelengths, a capability that only ISO offers. These programs have the aim of understanding the disk structure and heating mechanisms, the disk evolution (with particular interest for the formation of gaps caused by companion stars or large planets) and dissipation. As an example of such studies, we present in this talk some preliminary results from a study of TTS in Chamaeleon (Beckwith et al, 1998).

## 2. SEDs of T Tauri Stars in Chamaeleon

The Chamaeleon sample includes 16 well known TTS. The positions of the stars on the HR diagram are shown in Fig. 1, together with evolutionary tracks and isochrones from D'Antona and Mazzitelli (1994). The 16 stars span approximately an age range from  $3 \times 10^5$  to  $10^7$  yrs; 6 are known binaries, and 5 are single (Chelli et al. 1988; Chen and Graham 1992; Ghez et al. (1997); Beckwith et al. 1998) For all 16 stars we measured broad-band fluxes in 11 filters, from 4.8  $\mu\text{m}$  to 200  $\mu\text{m}$ , with an aperture of 52 arcsec.

Although the calibration uncertainty which affects these observations is still large, some general features emerge clearly from the data. If we compare the SED to the predictions of a passively heated (i.e., with no accretion), geometrically thin disk, we find that in all stars the emission at short wavelengths is consistent with the disk model (including, perhaps, the presence of inner holes for some

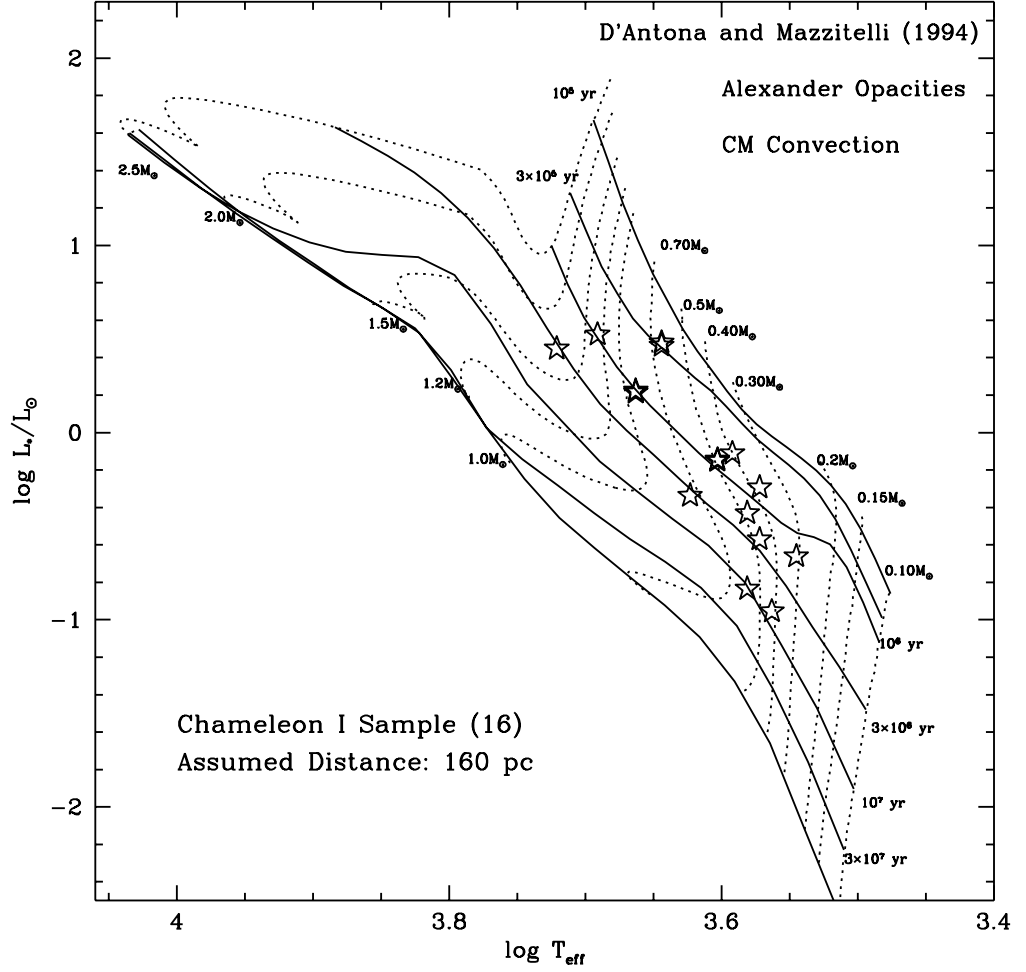


Figure 1. Location of the TTS in Chamaeleon in the ISO sample of Beckwith et al. (1998) on the HR diagram. Also shown are the D'Antona and Mazzitelli (1994) evolutionary tracks for stars of different mass (dotted lines; each track is labelled with the corresponding mass value) and isochrones (solid lines).

objects). In contrast, at long wavelengths the observed fluxes are much larger than the disk model predicts, by a factor from 5 to 50, depending on the star. The transition seems to occur at  $\lambda \sim 10 \mu\text{m}$ .

The long wavelength excess is seen in all 16 stars, including those that have very small excess emission at short wavelengths. The most extreme case in our sample is that of CS Cha (see Fig. 2), which shows no evidence of emission above the photospheric level at  $\lambda \lesssim 10 \mu\text{m}$ . Nevertheless, this star has a rather strong excess at longer wavelengths (about a factor of 10 at  $100 \mu\text{m}$  with respect to the prediction of a passive disk). CS Cha has been searched for companions by Ghez et al. (1997) in the separation range 0.1-12 arcsec and found to be single. If its extreme SED is interpreted as the emission of a circumstellar disk, then the inner disk must have dissipated up to a distance of about 0.3 AU from the star.

Objects with optically thin inner disks and optically thick remnant outer disks such as CS Cha are relatively rare (Skrutskie et al. 1990; Wolk & Walter 1996). This suggests that the timescale for transition from an inner accretion disk to a remnant passive disk is very short ( $\lesssim 10^6$  years).

### 3. $10 \mu\text{m}$ Silicate Feature in TTS

For 8 of the TTS in Chamaeleon for which we measured the SED, we also obtained PHOT-S low-resolution spectra in the  $10 \mu\text{m}$  region. In 4 cases out of 8 we detect the silicate feature in emission, with values of the peak over continuum ratios as high as  $\sim 3$ . We list the 8 stars in Table 1; a “y” in Column 2 indicates that the silicate feature is clearly in emission, a “n” that we see continuum emission only. In no case do we see the silicate feature in absorption. Table 1 gives also the luminosity and spectral type of the stars. In the last column, we note the presence or absence of companions from the references listed above. Fig. 3 shows the PHOT-S spectrum between 6 and  $12 \mu\text{m}$  of the star CT Cha.

The presence of the silicate feature in emission in a relatively large number of TTS is not new. In 1985 Cohen and Witteborn (1985) published a survey of  $10 \mu\text{m}$  spectra for pre-main-sequence stars. 19 of the 27 TTS in their sample showed the silicate feature in emission, 7 in absorption, 1 a continuum spectrum. In several cases, the ratio peak/continuum was  $\sim 2 - 3$ . A similar ratio ( $\sim 3$ ) was observed in the TTS Elias 28 in Ophiuchus (Hanner et al. 1995).

The presence of the silicate feature in emission reveals the existence in the immediate environment of the TTS of optically thin, relatively hot dust. Its intensity (both the absolute value and the ratio of the peak intensity to the adjacent continuum) can provide us with extremely interesting information on the properties of the disk, as we illustrate in the following of this section.

Let us assume, for simplicity, that the TTS dust opacity in the  $10 \mu\text{m}$  region does not differ much from that in the diffuse interstellar medium. Then the ratio of the peak ( $\kappa_{sil}$ ) to continuum ( $\kappa_{cont}$ ) opacity is about 3.5 (Draine and Lee 1984). This is the maximum contrast that one can expect to observe, and it is close to the values observed in several stars. The simplest case one can consider is that of an isothermal layer of dust at temperature  $T$  and optical depth  $\tau_\nu$ . At any given frequency  $\nu$ , the observed intensity is given by  $I_\nu = B_\nu(T) (1 - e^{-\tau_\nu})$ .

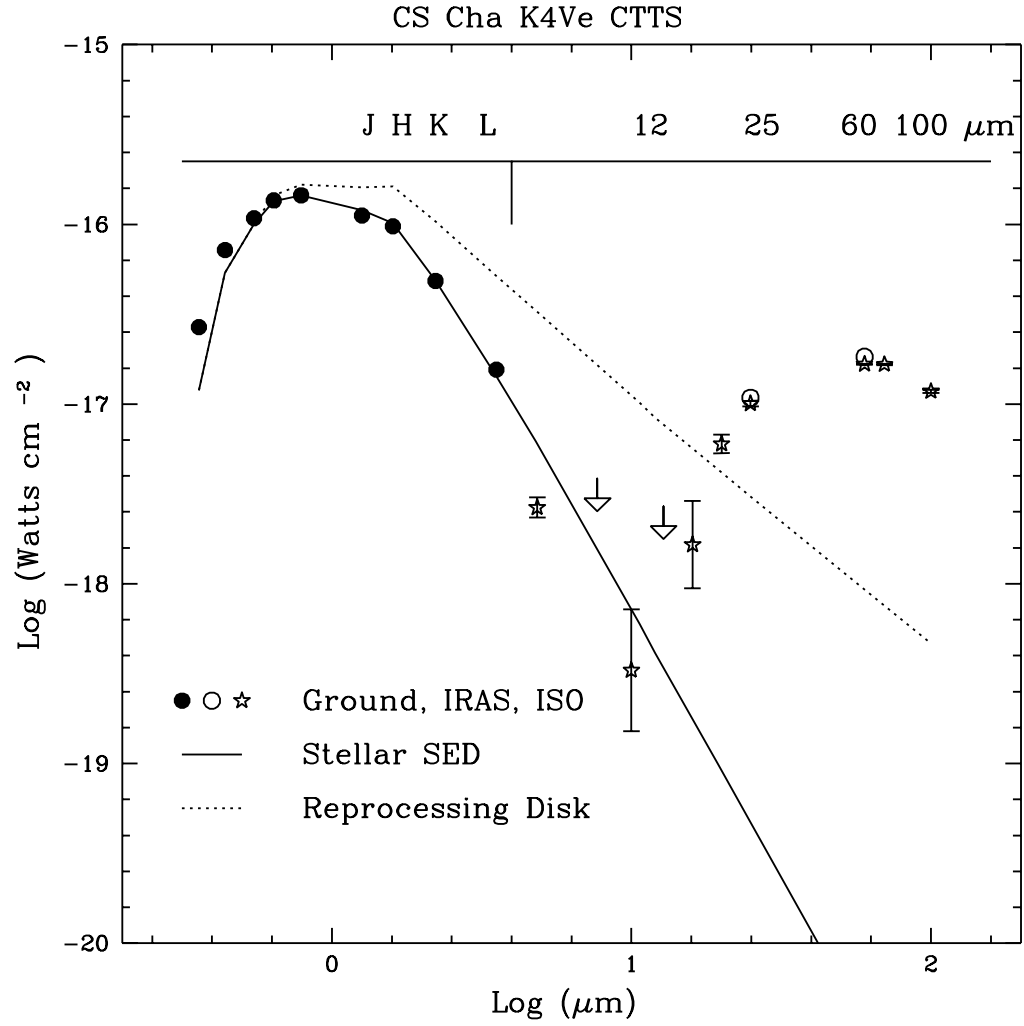


Figure 2. CS Cha SED. The ISO measurements are shown by stars. The two arrows denote upper limits from ISO observations. Filled circles are ground-based photometry. Open circles are IRAS measurements at 25 and 60  $\mu\text{m}$ . The solid curve shows the SED of the stellar photosphere; the dotted curve the model prediction for a standard reprocessing disk seen face-on.

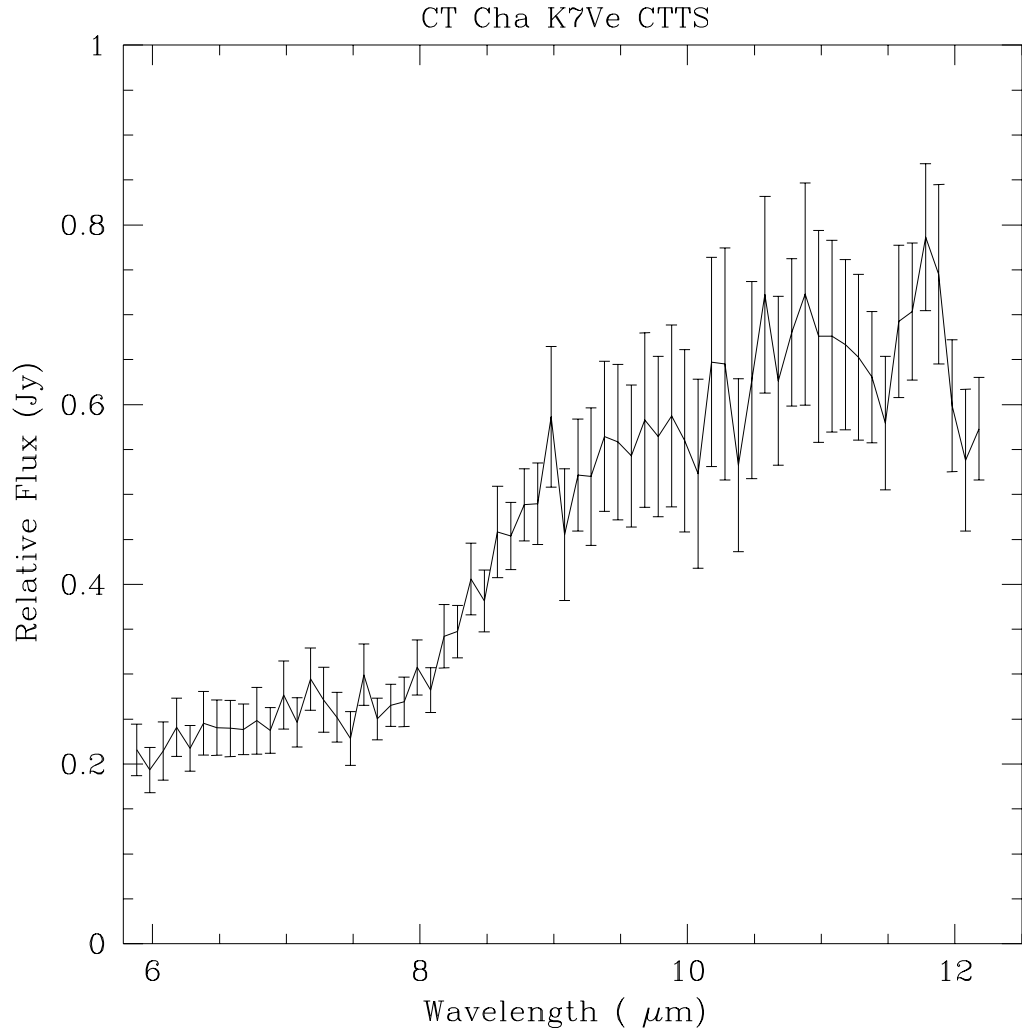


Figure 3. PHOT-S spectrum in the region 6 to 12 $\mu\text{m}$  of CT Cha. The absolute calibration of the continuum level may be uncertain by 30% or more.

Table 1. Chamaeleon TTS with PHOT-S Spectra

Star	Silicate Em.	Log( $L/L_{\odot}$ )	ST	Close Companions
CT Cha	y	-0.15	K7Ve	2.5''
Glass I	y	0.21	K4Ve	2.5'' (IRc)
LkH $\alpha$ 332-20	y	0.52	K2Ve	Sing.
SX Cha	y	-0.29	M0.5Ve	2.1'' (IRc)
VZ Cha	n	-0.34	K6Ve	Sing.
WX Cha	n:	-0.11	K7Ve	0.8''
XX Cha	n	-0.95	M1Ve	?
VW Cha	n	0.47	K5Ve	0.7''/16''

If  $\tau_{sil}, \tau_{cont} \gg 1$ ,  $I_{\nu} \sim B_{\nu}(T)$ , and the observed spectrum will just be that of a black-body at  $T$ . An emission feature can only be seen when  $\tau_{sil}, \tau_{cont} \ll 1$ ; in this case, however,  $I_{\nu} \sim B_{\nu}(T) \tau_{\nu} \ll B_{\nu}(T)$ , and both continuum and feature may be too weak to be detected. The best possibility of detecting a *strong* silicate feature in *emission* requires an optical depth at the peak of the silicate feature  $\tau_{sil} \sim 0.5$  (i.e.,  $A_V \sim 5$ ). Note, however, that the feature will appear slightly weaker, with respect to the continuum, than in the dust cross section. If  $\kappa_{sil}/\kappa_{cont} = 3.5$  and  $\tau_{sil} \sim 0.5$ , then  $I_{sil}/I_{cont} \sim 3$ .

If the slab of dust is not isothermal, the emerging spectrum depends not only on the optical depth and temperature gradient, but also on the location of the heating source with respect to the observer. Fig. 4 shows the spectra emerging from a slab of dust of increasing optical depth when the observer sees the dust slab from its cool side (bottom panel) and from its hot side (top panel). In TTS, we can expect the first situation if the star+disk system is surrounded by a (quasi)spherical, optically thin envelope of dust; the second may correspond to cases where the layer of dust is heated by the stellar radiation “from above”, as in a disk atmosphere. We can see from Fig. 4 that both cases can produce emission in the silicate feature. However, in the first case (i.e., when the dust layer is seen from its cold side), the ratio of the peak/continuum intensity is  $\sim \kappa_{sil}/\kappa_{cont}$  only for low values of the optical depth (as in the isothermal case), when both feature and continuum are quite weak. As  $\tau_{sil}$  increases, the colder foreground dust absorbs the emission of the hotter dust in the background until, for  $\tau_{sil} \gtrsim 2$ , the feature is seen in absorption. In other words, a ratio  $I_{sil}/I_{cont} \sim \kappa_{sil}/\kappa_{cont}$  is found only when the feature and the continuum are both very weak. On the contrary, when the slab is seen from its bright side, the strength of the feature increases with  $\tau_{sil}$ , and the condition  $I_{sil}/I_{cont} \sim \kappa_{sil}/\kappa_{cont}$  is verified also for large values of  $\tau$ , when both feature and continuum are strong.

There are few calculations of the expected infrared emission in TTS which include predictions of the intensity of the  $10\mu\text{m}$  silicate feature. Natta (1993) computes models where an optically thin spherical envelope of dust surrounds a star+standard disk system; the envelope spectrum shows the silicate feature in emission, with a ratio  $I_{sil}/I_{cont} \sim 3$ ; however, at these wavelengths the envelope emission is only a fraction of the emission of the optically thick disk in its centre, and the intensity of the feature in the resulting spectrum is only  $\sim 35\%$  of the

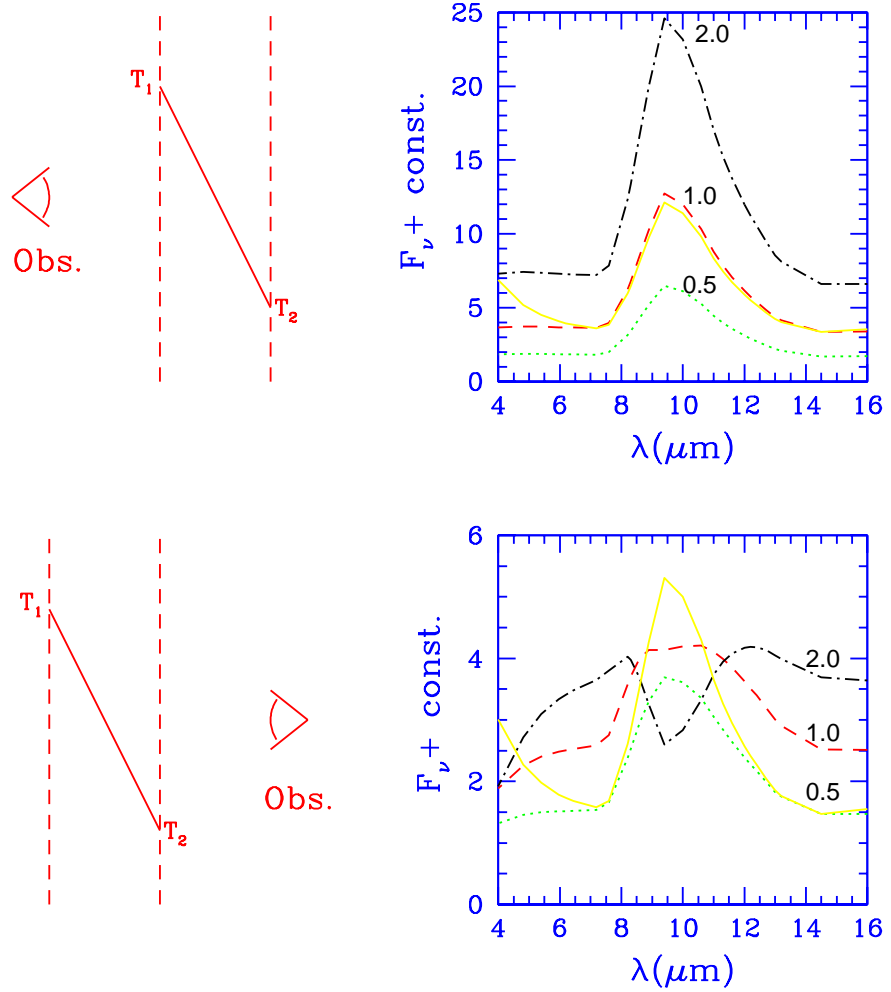


Figure 4. Emergent intensity of the  $10\mu\text{m}$  silicate feature from homogeneous, plane parallel slabs seen from the hotter side (top panel) and from the colder side (bottom panel). The temperature decreases as  $R^{-0.5}$  from  $T_1=1000$  K to  $T_2=100$  K. A sketch of the geometry is given on the left side of each panel; the resulting spectrum is shown on the right. In each case, we show the spectrum corresponding to three different optical depth at the wavelength of the peak of the feature,  $\tau_{\text{sil}} = 0.5, 1$  and  $2$ , as labelled. In both panels the solid curve shows the adopted opacity  $\kappa_\nu$  as a function of  $\lambda$  (arbitrarily normalized).



continuum. More recently, Chiang and Goldreich (1997) compute the SED of an hydrostatic, radiative equilibrium model of a passive disk; in this model, the disk is surrounded by an optically thin layer of superheated dust, which, when seen face-on, is reminiscent of the layer of dust "seen from the hot side" we have shown in Fig. 4, top panel. As expected, the predicted ratio  $I_{sil}/I_{cont} \sim 3$ . The continuum emission in the  $10\mu\text{m}$  region is quite strong, and the overall SED appears flat over a large range of wavelengths. A different model is proposed by Mathieu et al. (1991,1995) for the star GW Ori. This double star shows a very strong silicate feature which lies in a dip of the continuum, and has a ratio peak/continuum of about 2.6. This is well accounted for by a model where a large region of the disk (from 0.17 to 3.3 AU) is cleared by the dynamical action of the companion star; a small amount of dust (having an optical depth at the peak of the silicate feature of about 0.6) is left in the region, and is heated by the star to  $T \sim 560$  K. In this way, the continuum emission of the optically thick disk is suppressed and the intensity of the silicate feature in the emerging spectrum is maximized. A typical feature of this model is that the continuum emission in the  $10\mu\text{m}$  region is lower than predicted by standard, optically thick disk models, and the silicate feature lies in a "valley" of the SED.

ISO observations, which yield simultaneous measurements of the silicate feature and of the continuum in the 5-25  $\mu\text{m}$  region with unprecedented wavelength coverage, should be capable of discriminating between different models.

#### 4. Summary

ISO observations will contribute to our understanding of disks around low-mass pre-main-sequence stars in various ways.

Several ISO programs plan to measure the SEDs of well-known TTS. We have discussed the importance of such programs for our understanding of the disk heating mechanisms, the disk evolution, the formation of gaps caused by the presence of companion stars or large planets and the disk dissipation using preliminary results from PHOT and PHOT-S observations of TTS in the Chamaeleon cloud. We have also discussed in some detail the importance of simultaneous observations of the  $10\mu\text{m}$  silicate feature and of the broad-band continuum in the 5-20  $\mu\text{m}$  wavelength interval.

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